Head Mounted Display Optics II

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EE 267 Virtual Reality
Lecture 8
stanford.edu/class/ee267/
Lecture Overview

• focus cues & the vergence-accommodation conflict

• advanced optics for VR with focus cues:
  • gaze-contingent varifocal displays
  • volumetric and multi-plane displays
  • near-eye light field displays
  • holographic near-eye displays

• AR displays
Magnified Display

\[ \frac{1}{d} + \frac{1}{d'} = \frac{1}{f} \]

- big challenge: virtual image appears at fixed focal plane!
- no focus cues
Importance of Focus Cues Decreases with Age - Presbyopia

Duane, 1912
Relative Importance of Depth Cues

- Depth contrast
- 0 - 2 m
- 2 - 30 m
- > 30 m

- Motion Parallax
- Relative Size
- Atmospheric Perspective
- Relative Density
- Relative Height

Convergence & Accommodation
Stereopsis

Horizon
Depth (m)
The Vergence-Accommodation Conflict (VAC)
Stereopsis (Binocular)

Oculomotor Cue

Vergence

Visual Cue

Binocular Disparity

Focus Cues (Monocular)

Accommodation

Retinal Blur

extraocular muscles

ciliary muscles

relaxed

contracted
Stereopsis (Binocular)

Oculomotor Cue

Vergence

Visual Cue

Binocular Disparity

Focus Cues (Monocular)

Accommodation

Relaxed

Contracted

ciliary muscles

extraocular muscles
Real World: Vergence & Accommodation Match!
Current VR Displays: Vergence & Accommodation Mismatch
Accommodation and Retinal Blur

Conventional Display

Virtual image of screen

- 0.25m (4D)
- 0.3m (3.33D)
- 0.35m (2.86D)
- 0.5m (2D)
- 0.7m (1.43D)
- 1 m
- 2m (0.5D)
- ∞ (0D)
Blur Gradient Driven Accommodation

Conventional Display
Blur Gradient Driven Accommodation

Conventional Display

0.25m (4D) 0.3m (3.33D) 0.35m (2.88D) 0.5m (2D) 0.7m (1.43D) 1m 2m (0.5D) ∞ (0D)
Blur Gradient Driven Accommodation

Conventional Display

0.25m (4D)  0.3m (3.33D)  0.35m (2.86D)  0.5m (2D)  0.7m (1.43D)  1 m  2m (0.5D)  → (0D)
Blur Gradient Driven Accommodation

Conventional Display

[Image of cartoon characters with a diagram showing various distances and accommodation numbers]
Blur Gradient Driven Accommodation

Conventional Display

![Image of cartoon characters with blurry vision](image)

Distance in meters:
- 0.25m (4D)
- 0.3m (3.33D)
- 0.35m (2.86D)
- 0.5m (2D)
- 0.7m (1.43D)
- 1m
- 2m (0.5D)
- ∞ (0D)

Virtual image of screen
Blur Gradient Driven Accommodation

Conventional Display

Accommodation-dependent Point Spread Functions

[Diagram showing accommodation-dependent point spread functions with distances marked: 0.25m (4D), 0.3m (3.33D), 0.35m (2.88D), 0.5m (2D), 0.7m (1.43D), 1m, 2m (0.5D), ∞ (0D)]
Real World:

Vergence & Accommodation Match!
Stereo Displays Today (including HMDs):

Vergence-Accommodation **Mismatch!**
Consequences of Vergence-Accommodation Conflict

- Visual discomfort (eye tiredness & eyestrain) after ~20 minutes of stereoscopic depth judgments (Hoffman et al. 2008; Shibata et al. 2011)

- Degrades visual performance in terms of reaction times and acuity for stereoscopic vision (Hoffman et al. 2008; Konrad et al. 2016; Johnson et al. 2016)

- Short-term effects: double vision (diplopia), reduced visual clarity
VR Displays with Focus Cues

1. Gaze-contingent Varifocal Displays
Fixed Focus Displays

\[ \frac{1}{d} + \frac{1}{d'} = \frac{1}{f} \]
Varifocal Displays

Magnified Display

\[
\frac{1}{d} + \frac{1}{d'} = \frac{1}{f}
\]

actuator \(\rightarrow\) vary \(d'\)

Lens

Display
Varifocal Displays

Magnified Display

Focus-tunable lens \( \rightarrow \text{vary } f \)

\[
\frac{1}{d} + \frac{1}{d'} = \frac{1}{f}
\]
Varifocal Displays - History

- M. Heilig “Sensorama”, 1962 (US Patent #3,050,870)
- S. Shiwa, K. Omura, F. Kishino “Proposal for a 3-D display with accommodative compensation: 3DDAC”, JSID 1996
- S. McQuaide, E. Seibel, J. Kelly, B. Schowengerdtt, T. Furness “A retinal scanning display system that produces multiple focal planes with a deformable membrane mirror”, Displays 2003
- S. Liu, D. Cheng, H. Hua “An optical see-through head mounted display with addressable focal planes”, Proc. ISMAR 2008

Manual focus adjustment:
- Heilig 1962

Automatic focus adjustment:
- Mills 1984

Deformable mirrors & lenses:
- McQuaide 2003, Liu 2008
Translation Stage

Padmanaban et al., PNAS 2017
Conventional Stereo / VR Display

- **Conventional**
  - Stereoscopic distance
  - Virtual image distance

- **Vergence**
- **Accommodation**
Removing VAC with Varifocal Displays

With Focus Cues

stereoscopic distance

virtual image distance

stereoscopic distance

vergence

accommodation
Task

Follow the target with your eyes
Accommodative Response

- Conventional
- Dynamic Focus

Padmanaban et al., PNAS 2017
Accommodative Response

Conventional

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Accommodation</th>
</tr>
</thead>
<tbody>
<tr>
<td>n = 59, mean gain = 0.29</td>
<td></td>
</tr>
</tbody>
</table>

Padmanaban et al., PNAS 2017
Accommodative Response

Padmanaban et al., PNAS 2017
Accommodative Response

Padmanaban et al., PNAS 2017
Do Presbyopes Benefit from Dynamic Focus?

Padmanaban et al., PNAS 2017
Do Presbyopes Benefit from Dynamic Focus?

Padmanaban et al., PNAS 2017
Do Presbyopes Benefit from Dynamic Focus?

Padmanaban et al., PNAS 2017
Do Presbyopes Benefit from Dynamic Focus?

Gain vs. Age

- Orange dots: conventional
- Green dots: dynamic

Response for Physical Stimulus
Heron & Charman 2004

Padmanaban et al., PNAS 2017
Gaze-contingent Varifocal Displays

- non-presbyopes: adaptive focus is like real world, but needs eye tracking!

Padmanaban et al., PNAS 2017
Gaze-contingent Varifocal Displays

Padmanaban et al., PNAS 2017
Gaze-contingent Varifocal Displays

Padmanaban et al., PNAS 2017
Gaze-contingent Varifocal Displays

Padmanaban et al., PNAS 2017
at ACM SIGGRAPH 2016
Oculus announces gaze-contingent varifocal display at F8, 05/2018

Video courtesy of Facebook/Oculus
Dunn et al. “Wide Field of View Varifocal Near-Eye Display using See-through Deformable Membrane Mirrors”, IEEE TVCG 2017
Summary

- Adaptive focus drives accommodation and can also correct for refractive errors (myopia, hyperopia).
- Gaze-contingent focus gives natural focus cues for non-presbyopes, but require eyes tracking.
- Presbyopes require fixed focal plane with correction.
VR Displays with Focus Cues

2. Multiplane Displays
Multiplane VR Displays

- Schowengerdt B, Seibel E (2006) True 3-d scanned voxel displays using single or multiple light sources. JSID
- Love GD et al. (2009) High-speed switchable lens enables the development of a volumetric stereoscopic display. Optics Express
- … many more …
Challenges of Multiplane VR Displays

- when implemented with focus-tunable optics & time-multiplexing in VR: *flicker*

- when implemented with multiple optically overlaid microdisplays in VR or multiple waveguides in AR: *system complexity and calibration*

- multifocal plane displays require image focal plane decomposition – computationally expensive

- decompositions are sensitive to eye position – also need eye tracking, so why not just do varifocal?
VR Displays with Focus Cues

3. Light Field Displays
Light Field Stereoscope

- Backlight
- LCD Panel
- Magnifying Lenses
- Thin Spacer & 2\textsuperscript{nd} panel (6mm)

Huang et al., SIGGRAPH 2015
Near-eye Light Field Displays

Idea: project multiple different perspectives into different parts of the pupil!
Target Light Field

Input: 4D light field for each eye
Multiplicative Two-layer Modulation

Input: 4D light field for each eye

Model Courtesy of Bushmills Irish Whiskey
Multiplicative Two-layer Modulation

Input: 4D light field for each eye

Model Courtesy of Bushmills Irish Whiskey
Multiplicative Two-layer Modulation

Input: 4D light field for each eye

Model Courtesy of Bushmills Irish Whiskey
Multiplicative Two-layer Modulation

\[ \text{minimize} \| \beta I - (\phi_1 t_1) \circ (\phi_2 t_2) \|^2 \]
\[ \{ t_1, t_2 \} \quad \text{s.t.} \quad 0 \leq t_1, t_2 \leq 1 \]

Reconstruction:
\[ t_1 \leftarrow t_1 \circ \frac{\phi_1^T(\beta I \circ (\phi_2 t_2))}{\phi_1^T(\mathbf{1} \circ (\phi_2 t_2)) + \epsilon} \]
for layer \( t_1 \)

Input: 4D light field for each eye

Model Courtesy of Bushmills Irish Whiskey

Tensor Displays, Wetzstein et al. 2012
Light Field Stereoscope

Traditional HMDs - No Focus Cues

The Light Field HMD Stereoscope

Huang et al., SIGGRAPH 2015
Light Field Stereoscope

Traditional HMDs - No Focus Cues

The Light Field HMD Stereoscope

Huang et al., SIGGRAPH 2015
Light Field Stereoscope

Traditional HMDs - No Focus Cues

The Light Field HMD Stereoscope

Huang et al., SIGGRAPH 2015

Model Courtesy of Paul H. Manning
Light Field Stereoscope

Traditional HMDs - No Focus Cues

The Light Field HMD Stereoscope

Huang et al., SIGGRAPH 2015

Model Courtesy of Paul H. Manning
Tensor Displays

Wetzstein et al., SIGGRAPH 2012
Vision-correcting Display

printed transparency

iPod Touch prototype

Huang et al., SIGGRAPH 2014
300 dpi or higher

Huang et al., SIGGRAPH 2014
Microlens-based Near-eye Light Field Displays

Thin VR version: Lanman and Luebke, 2013

Optical see-through AR version: Hua and Javidi, 2014

• biggest downside: usually low resolution

• limited by spatio-angular resolution tradeoff and, more fundamentally, also diffraction
4. Holographic Near-eye Displays
Holographic Near-eye Displays

- recently great image quality demonstrated!
- limited by space-bandwidth product: either small field of view + “large-ish” eyebox or vice versa, but not both
- interference in users’ eyes may be a problem
Holographic Near-eye Displays

**Challenge**: low image quality due to mismatch between physical optics and simulation.
Neural Holography

Input: RGBD

Output: SLM phase

Camera-calibrated Wave Propagation Model

Physical Optics

Masked Image

Layer Masks

Camera-calibrated Wave Propagation Model

[Peng et al., SIGGRAPH Asia 2020; Choi et al., SIGGRAPH ASIA 2021]
Gerchberg–Saxton
Neural Holography 2020 Results

[Peng et al., SIGGRAPH & SIGGRAPH Asia 2020]
3D Neural Holography on Emerging MEMS Phase SLMs

[Choi, Gopakumar et al., SIGGRAPH 2022]
3D Neural Holography on Emerging MEMS Phase SLMs

[Choi, Gopakumar et al., SIGGRAPH 2022]
Additional Benefits of Holographic Near-eye Displays

Thin VR Display Form Factors

Other:

• Light-efficient AR Displays
• Prescription correction (including astigmatism and higher-orders)
• Correcting optical aberrations

Maimone et al., SIGGRAPH 2020
Kim et al., SIGGRAPH 2022
Summary of AR/VR Displays with Focus Cues

- focus cues in VR/AR are challenging
- adaptive focus can correct for refractive errors (myopia, hyperopia)
- gaze-contingent focus gives natural focus cues for non-presbyopes, but require eyes tracking
- presbyopes require fixed focal plane with correction
- multiplane displays require very high speed microdisplays or multiple optically overlaid displays
- light field and holographic displays may be “ultimate” displays in the longer-run → need to solve a few “issues” first
Overview of Optical See-through AR Displays
Thin Beam Combiner?
Thin Beam Combiner!
Thin Beam Combiner!

Critical angle $\theta_c$ : smallest angle of incidence that yields total reflection

Snell’s laws of refraction: $n_1 \sin \theta_1 = n_2 \sin \theta_2 \rightarrow \theta_c = \sin^{-1} \left( \frac{n_2}{n_1} \right)$
OST AR - Case Studies
Google Glass
Meta 2

- larger field of view (90 deg) than Glass
- also larger device form factor
Microsoft HoloLens
- diffraction grating
- small FOV (30x17), but very good image quality
Microsoft HoloLens 2

- laser-scanned waveguide display
- claimed 2K resolution per eye (2560x1440), probably via “interlaced” scanning
- field of view: 52° diagonally (3:2 aspect, 47 pixels per visual degree)

AR Lightguides and Waveguides

https://arvrjourney.com/understanding-waveguide-the-key-technology-for-augmented-reality-near-eye-display-part-ii-fe4bf3490fa
Challenges: Eye Box vs Field of View
Challenges: Eye Box vs Field of View

- need small entrance pupil (small device) and large exit pupil (large eye box) - pupil needs to be magnified
Challenges: Eye Box vs Field of View

- need small display (small device) but large field of view – image needs to be magnified
Challenges: Eye Box vs Field of View

- pupil needs to be magnified
- image needs to be magnified

Can’t get both at the same time – etendue!
Challenges: Eye Box vs Field of View

- possible solutions: exit pupil replication (loss of light), live with small FOV (not great), dynamically steer eye box (mechanically difficult), ..
Exit Pupil Expansion

(a) 1D Pupil Expansion

(b) 2D Pupil Expansion with Turn Grating

(c) 2D Pupil Expansion with 2D Grating
Challenges: Chromatic Aberrations

- thin grating couplers create chromatic aberrations
Challenges: Chromatic Aberrations

(a) Single-layer Waveguide

(b) Multi-layer Waveguide

https://arvrjourney.com/understanding-waveguide-the-key-technology-for-augmented-reality-near-eye-display-part-ii-fe4bf3490fa
Challenges: Chromatic Aberrations

volume holographic couplers, e.g. TruLife Optics

stacked waveguides

- all solutions have their own problems: ease of manufacturing, yield, robustness, cost, ...
Occlusions

Case 1: digital in front of physical
→ difficult: need to block real light!

Case 2: physical in front of digital
→ easy: don’t render digital object everywhere
Video-based AR: ARCore, ARKit, ARToolKit, …
Next Lecture: Inertial Measurement Units I

• accelerometers, gyros, magnetometers
• sensor fusion
• head orientation tracking